# UNITED STATES
# NAVAL POSTGRADUATE SCHOOL


## THESIS

CREEP OF COPPER

AT

INTERMEDIATE AND LOW TEMPERATURES

By

Arnold A. Hahnfeld

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## ABSTRACT

A review of a few of the many equations for describing the creep curve is given, showing the need for a valid and broader theory for creep. One of these equations, set forth by Dorn[22], is partially tested in the intermediate and low temperature regions using experimental data for vacuum melted copper, and values for the activation energy term of this equation are determined. The method of determination and some of the difficulties involved in this determination are set forth. Additional values for the activation energy term as determined by Tietz and Dorn[23] are included. The composite data indicate that the activation energy in the temperature region investigated is a function of temperature, decreasing with a decrease in temperature.

TABLE OF CONTENTS


| | Page |
|---|---|
| ABSTRACT | ii |
| LIST OF SYMBOLS | v |
| INTRODUCTION | 1 |
| EXPERIMENTAL PROCEDURE | |
| Development | 7 |
| Equipment | 8 |
| Source and Treatment of Error | 15 |
| Low Temperature Problems | 18 |
| RESULTS AND CONCLUSIONS | 23 |
| ACKNOWLEDGMENTS | 27 |
| BIBLIOGRAPHY | 28 |
| APPENDIX - TABULAR PRESENTATION OF EXPERIMENTAL DATA | 31 |

## LIST OF ILLUSTRATIONS


| | | Page |
|---|---|---|
| 1. | Creep Testing Apparatus | 9 |
| 2. | Details of Specimen Cage | 10 |
| 3. | Details of Extensometer | 11 |
| 4. | Specimen Detail | 13 |
| 5. | Low Temperature Equipment | 21 |
| 6. | Activation Energy versus Temperature | 25 |


## LIST OF TABLES


| | | |
|---|---|---|
| I | Material Analysis | 14 |
| II | Low Temperature Baths | 19 |
| III | Tabular Presentation of Results | 24 |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $t$ | Time | minutes |
| $T$ | Temperature, absolute | $^{o}K$ |
| $\varepsilon$ | Strain at time t | inches/inch |
| $\dot{\varepsilon}$ | Instantaneous strain rate | 1/minutes |
| $R$ | Gas Constant | cal/gm-mol $^{o}K$ |
| $\Delta F$ | Free energy of activation | cal/gm-mol |
| $\Delta H_c$ | Activation energy for creep | cal/gm-mol |
| $\Delta H_{1,2}$ | Mean, or approximate, activation energy for the temperatures 1, 2. | cal/gm-mol |
| $\Delta S$ | Entropy of activation | cal/gm-mol $^{o}K$ |
| $S$ | Structure parameter | 1/minutes |
| $\beta$ | Stress parameter | sq in/lb |
| $\sigma$ | Applied stress | lb/sq in |
| A,B,C | Constants | |
| M,N | Constants, at constant temperature | |
| r | Minimum creep rate | 1/minutes |
| $\gamma$ | Coefficient of transient creep | |
| $K$ | Coefficient of steady state creep | |
| f | Functional symbol | |
| x,y,z | Variables | |
| e | Base of Napierian logarithms | |
| ln | The Napierian logarithm | |

A small number of additional symbols are defined in the text.

# INTRODUCTION

Creep may be defined from many points of view. It has been defined as the time dependent part of the deformation which accompanies the application of stress to a solid[1]*. It has also been defined as the flow or plastic deformation of metals held for long periods of time at stresses lower than the normal yield strength[2]. These definitions reflect the views of the metallurgist and the design engineer, respectively. They reflect slightly different aspects of a complex, little understood, mechanism. A number of theories from both the micromechanistic and the phenomenological approaches have been advanced; some of these have been rejected, while others are still being tested. None of these theories are complete and none are entirely satisfactory.

The compilation of accurate, useful, creep data is a slow and painful process. Tests may be run from 1,000 to 10,000 hours (40 days to 14 months), in the usual case, and in many cases much longer. In order that data be more rapidly gathered and extrapolated more successfully, a valid theory for creep is required, useful over more than limited regions of temperature and stress and useful for a broad range of materials.

The creep curve (strain versus time) has been approached

*Superscripts in parenthesis refer to the bibliography.

mathematically by many investigators over the past fifty years. A few of the many equations proposed to correlate creep data are set forth herein. These constitute a small sampling of the total number proposed, but are believed to show the nature and limitations of previous work. As early as 1905 Phillips[3] suggested that for short times and at constant load the equation

$$\varepsilon = A + B \log t \tag{1}$$

could be fitted to the creep curve of metals. Andrade[4,5] proposed the equation

$$\ell = \ell_o (1 + \gamma t^{1/3}) e^{\kappa t} \tag{2}$$

where $\ell$ = length at time t, $\ell_o$ = a constant (not necessarily the original length). This equation, or modifications thereof, has been and is used extensively for curve fitting of experimental creep data. In 1950, Wyatt[6] found that equation (1) best fitted data on copper and aluminum at low temperatures. At higher stresses there was some divergence from this equation. At higher temperatures the equation which best fitted the data was

$$\varepsilon = A + B \log t + \gamma t^{1/3}. \tag{3}$$

Wyatt appears to be the first to show that different equations fit the data for the same metals under different conditions of stress and temperature[7]. Hazlett and Parker[8], in 1953, set forth the equation

$$\varepsilon - \varepsilon_o = A t^B \qquad (4)$$

where $\varepsilon$ = total true strain. $\varepsilon_o$ = instantaneous strain on loading. Bragaw and Orowan[9], in 1953, found various equations applicable dependent upon the temperature and the stress, and to some extent on the material (Electrolytic Tough Pitch Copper and 2S Aluminum). Their equations are combinations of terms from equations (1) and (2).

Sometime before 1938, Nadai[10] related strain rate and stress by the equation

$$\dot{\varepsilon} = A \sinh \sigma/B . \qquad (5)$$

In 1936, Eyring[11] proposed his "Theory of Activated Complexes" or "Rate Process Theory" which applied to chemical reactions only. Subsequently, Kauzmann[12], in 1941, and Dushman[13], in 1944, working independently, also applied the theory to plastic deformation of metals. They presented practically the same equation,

$$r = M e^{-\Delta F/RT} \sinh (N\sigma) \qquad (6)$$

Creep rupture data has been correlated by the equations and methods of Machlin and Nowick[14], Grant and Bucklin[15], and Larson and Miller[16]. Additional insight into the theory may be gained from the work of Sietz and Read[17], Mott[18], Nabarro[19], Orowan[20]and Cottrell[21].

Dorn and co-workers[22], present the equation

$$\dot{\varepsilon} = S e^{-\Delta H_c/RT} e^{\beta\sigma} \qquad (7)$$

for the correlation of creep data over the high temperature region* where crystal recovery is known to be rapid. At low stresses the $\beta\sigma$ term is replaced by some other function, probably 2 $\sinh\beta\sigma$ since the equation must reduce to zero for zero stress. In the case of aluminum, $\Delta H_c$ is reported to be insensitive to minor amounts of solid solution alloying additions, to the presence of dispersions of stable intermetallic compounds, to cold work, and grain size, and constant independent of stress, strain, and temperature. From this and other evidence it was deduced that $\Delta H_c$ is a property of the material not sensitive to changes in structure. Correlations obtained suggested that for relatively pure metals, in the high temperature region, this activation energy is nearly equal to that of self-diffusion. The activation energy for self-diffusion of copper is reported[23] as 48,000 cal/gm-mol. An extension of this investigation in the intermediate and low temperature regions was carried out by Tietz and Dorn[24], and Naczkowski[25], and is still under intensive investigation at the University of

*The high temperature region is defined for this purpose as greater than 0.45 of the melting point in degrees Kelvin. Intermediate and low temperatures are likewise defined as the temperature between room temperature and high temperature, and between room temperature and absolute zero, respectively. The limits of intermediate and low temperature are relative and the definition of these terms is set forth for the purpose of this thesis only.

California, at Berkeley.

The parameter, $\beta$, is arrived at by utilizing the expression $\dot{\varepsilon} = S' e^{\beta\sigma}$ and obtaining the slope of the $\sigma$ versus log $\dot{\varepsilon}$ curves, at various constant temperatures, for constant structure. The curves in all cases were linear. This parameter was investigated for high purity aluminum. and aluminum base solid solution alloys, in the high temperature region only and found to be independent of creep structure for a given material. The term $1/\beta$ increases almost linearly with atomic per cent of solute element. It appears that no similar investigation has been undertaken for other metals.

The structure parameter, S, is the most complex and most obscure of the parameters. It is a function of the stress-strain history of the specimen, and all the effects of structure are felt to be wholly contained in this parameter.

In the high temperature region the activation energy for creep, where it has been determined, has been reported by Dorn[22] to be a constant, approximating the value for self-diffusion. At lower temperatures this is apparently no longer so. Tietz and Dorn[24] working with OHFC copper in the region 348°K to 469°K find $\Delta H_c$ to be 37,000 $\pm$ 3,000 cal/gm-mol independent of stress and strain. a value substantially lower than the self-diffusion value. Naczkowski[25] working with pure magnesium found that the activation energy for creep of this material varied linearly from 9,100 cal/gm-mol to 16,200 cal/gm-mol, in the region 200°K to 260°K.

For the purpose of this thesis it is postulated that the temperature dependent factor of strain rate may be represented as $e^{-f(T)/RT}$ where clearly f(T) has the dimensions of energy. Dorn has associated[22] this quantity with the activation energy ($\Delta H$) and has shown good experimental correlation with the activation energy for self-diffusion, in the high temperature region. Recently he has indicated[26] that the activated Gibbs free energy, $\Delta F = \Delta H - T\Delta S$, should be used in the rate equation instead of the activation energy ($\Delta H$). With the assumption that the temperature dependent factor is indeed $e^{-\Delta F/RT}$ the strain rate expression may be reduced to a relation for the activation energy involving only the temperature and the strain rate, as will be shown in a subsequent section. The activation energy is thus subject to experimental determination. Utilizing this relation the activation energy for creep of vacuum melted copper was determined at temperatures in the intermediate and low temperature regions, for various conditions of stress. The activation energies thus determined are presented, along with those of Tietz and Dorn.

## EXPERIMENTAL PROCEDURE

### Development

A specimen is placed in a constant temperature environment at a temperature $T_1$ and is permitted to creep under constant load. At some time t, with a corresponding strain $\varepsilon$, the environment is rapidly changed to temperature $T_2$ while creep is allowed to continue. The structure developed at a strain $\varepsilon$ and temperature $T_1$ would be retained at temperature $T_2$ at the instant of change, since no phase changes are involved. The stress, $\sigma$, which continually increases during the test is also the same at the instant of change. Thus the only variables in equation (7) at the instant of change are contained in $e^{-\Delta H_c/RT}$. If the change could be made in a time interval approaching zero and temperature equilibrium established immediately, then equation (7) leads to

$$\dot{\varepsilon}_1 e^{\Delta H_c/RT_1} = \dot{\varepsilon}_2 e^{\Delta H_c/RT_2}$$

However, in the temperature region under consideration, $\Delta H$ is not believed to be a constant but to be a function of temperature. It is further believed that in the original equation $\Delta H$ should be replaced with $\Delta F$[26], where $\Delta F = \Delta H - T\Delta S$. Equation (7) then becomes $\dot{\varepsilon}_1 = S e^{-\Delta F_1/RT_1} e^{\beta\sigma}$ and at the time t:

$$\dot{\varepsilon}_1 e^{\Delta F_1/RT_1} = \dot{\varepsilon}_2 e^{\Delta F_2/RT_2}$$

If $\dot{\varepsilon} e^{\Delta F/RT} = C_1$ then

$$R \ln \dot{\varepsilon} = -\frac{\Delta F}{T} + C_2$$ and

$$R\, d(\ln \dot{\varepsilon}) = -d(\Delta F/T)$$

For a constant pressure process $d\left(\frac{\Delta F}{T}\right) = \Delta H\, d(1/T)$

and $R\, d(\ln \dot{\varepsilon}) = -\Delta H\, d(1/T)$

Letting a finite difference replace the differential, the following is obtained:

$$R(\ln \dot{\varepsilon}_2 - \ln \dot{\varepsilon}_1) = -\Delta H_{1,2}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad \text{and}$$

$$\Delta H_{1,2} = R\left(\frac{T_1 T_2}{T_2 - T_1}\right) \ln \frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} \qquad (8)$$

At the time t, $\Delta H_{1,2}$ may be evaluated by obtaining the creep rates associated with the two temperatures. This is done by extrapolation to the time t.* All externally controllable variables have been controlled. Specimen scatter has been eliminated since only one specimen is used for a complete determination.

Equipment

The creep machines utilized are shown in Figure 1. The lever arm was calibrated over the range of arc used and determined to be 10.0:1. This was accomplished with a Type U Load Cell and Baldwin SR-4 Indicator. During testing, one end of the lever was attached to the specimen by means of an extensometer; the other end was weighted. The cage (Figure 2), specimen, and lower end of the extensometer system (Figure 3) were immersed in the constant temperature baths and insulated

*The technique used in the determination of strain rates was the same technique employed by Tietz and Dorn, and Naczkowski. It is set forth in detail in references (24) and (25).

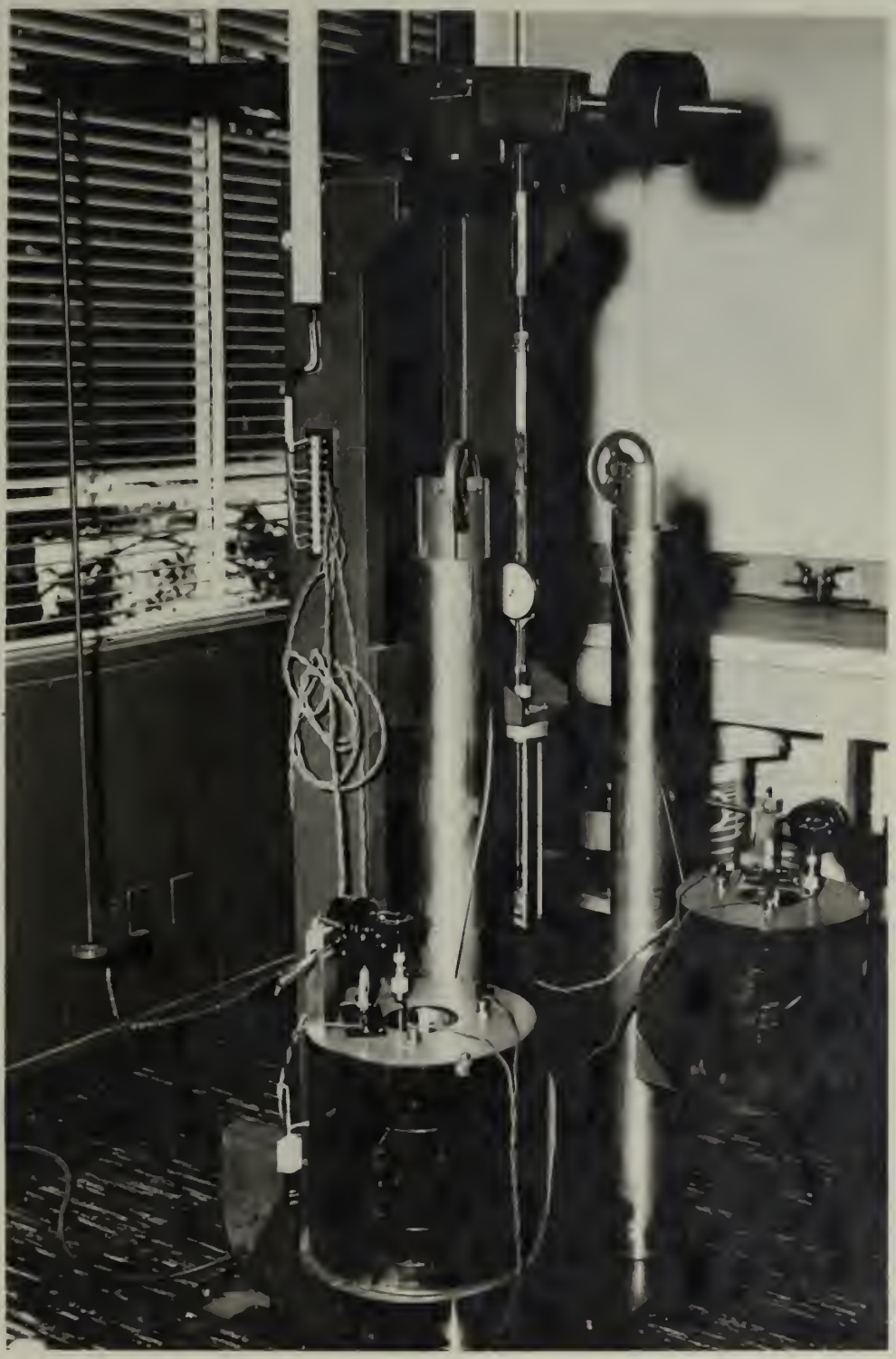

Figure 1

CREEP TESTING APPARATUS

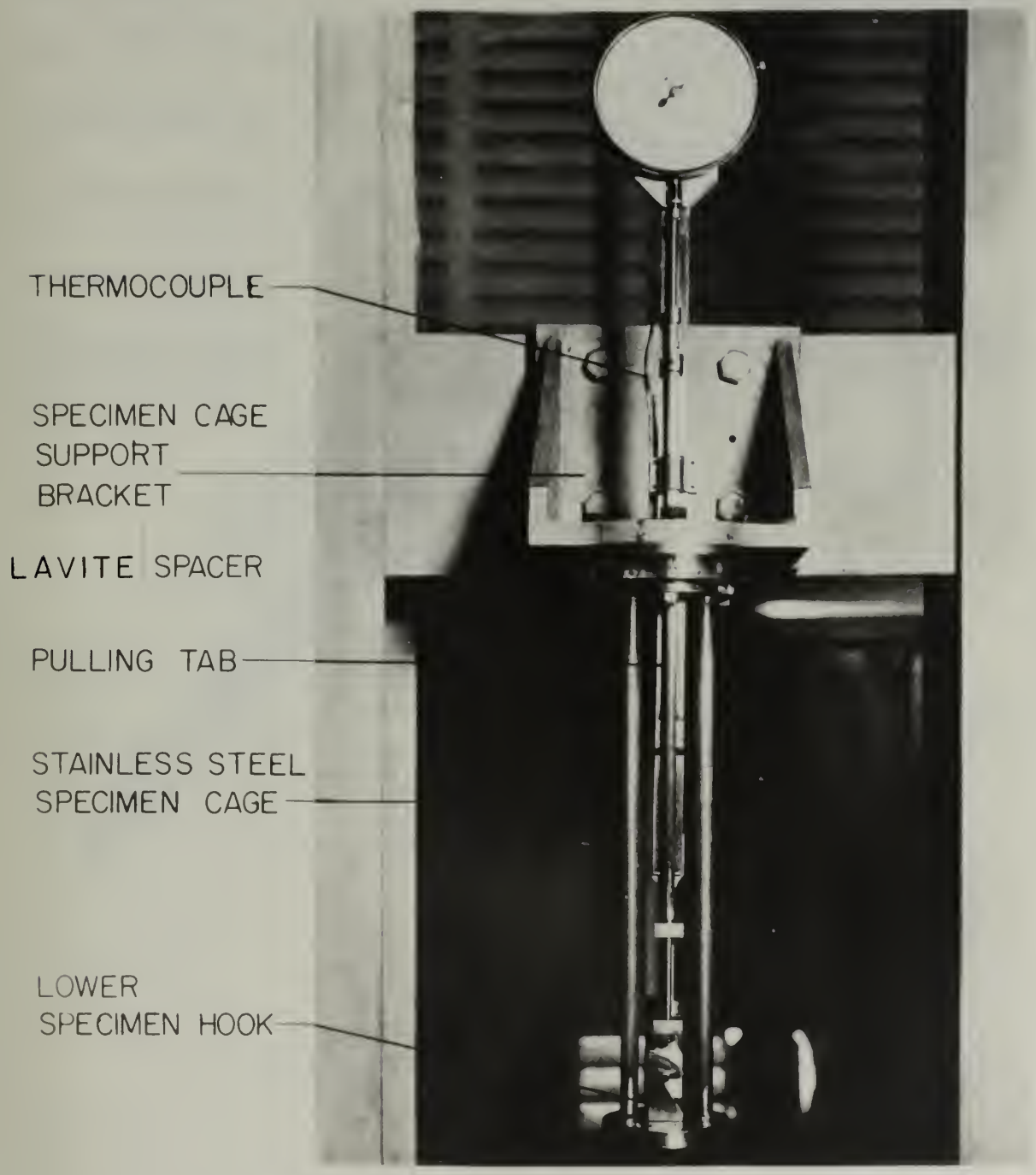


FIG. 2 DETAILS OF SPECIMEN CAGE

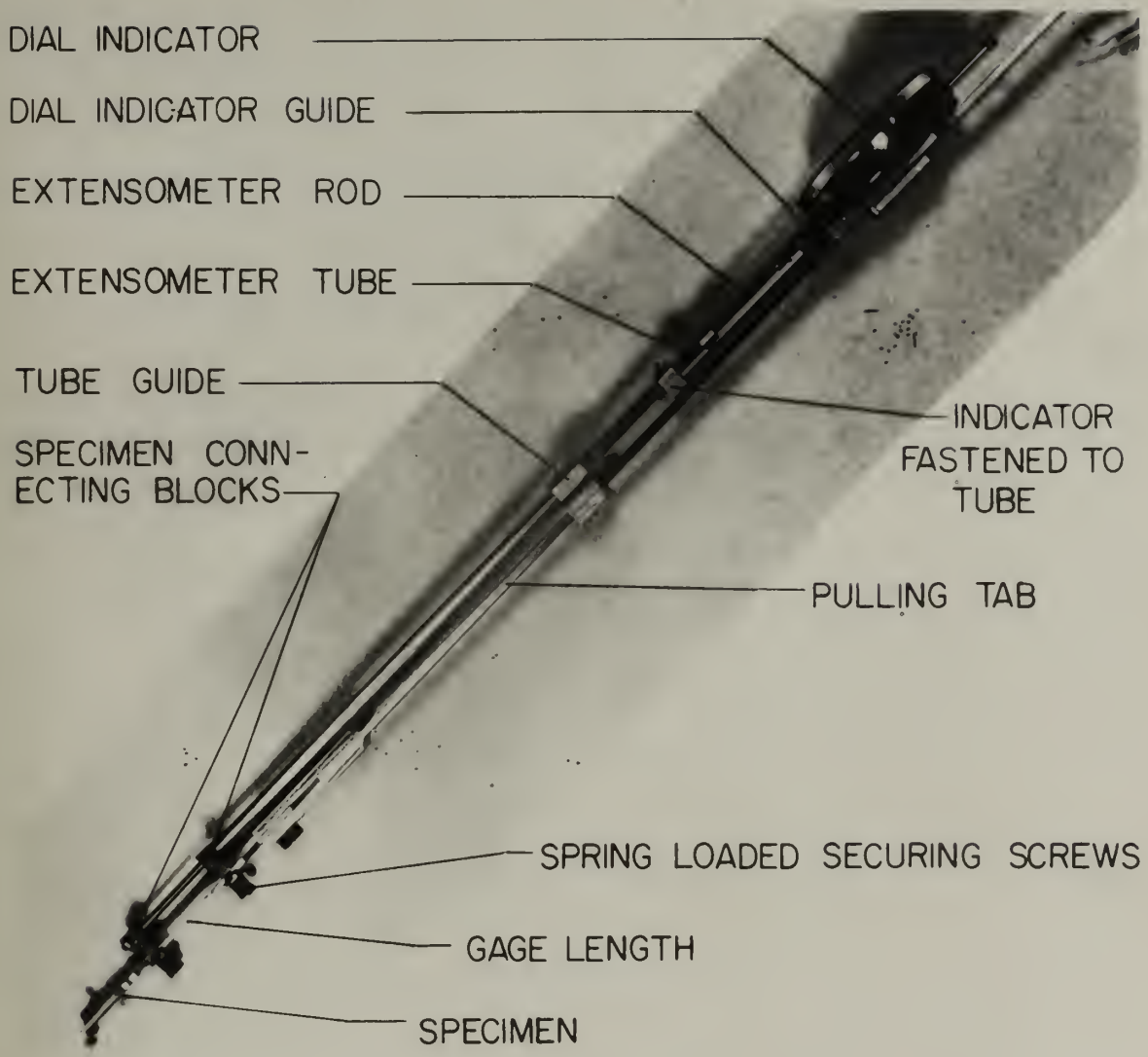


FIG. 3 DETAILS OF EXTENSOMETER

from the atmosphere where necessary. Bath platform, with counterweights, were designed to facilitate rapid bath changes. The specimen dimensions are shown in Figure 4. Specimens were machined from cold-rolled copper strip supplied by Vacuum Metals Corporation and represented to be of 99.99% purity. No analysis was received with the material. Independent analysis by chemical assay resulted in a finding of at least 99.97% copper. Results of spectrographic analysis are shown in Table I. Specimens were machined with their tensile axis paralled to the rolling direction. They were annealed in a helium atmosphere at 500°C for a period of two hours, with a resultant grain size of 0.015 mm. During the intermediate temperature tests silicone oil supplied the environment, Dow Corning 510 Fluid being utilized. Temperature control for these tests was maintained electrically by means of a bank of resistors and a mercury regulator. The regulator consisted of a bulb reservoir of relatively large volume and a capillary in which two electrodes were spaced. Sufficient power was supplied to the system to cause the temperature to increase gradually, resulting in an increasing height of mercury in the capillary. When the mercury column rose to a height sufficient to touch the higher electrode, a second circuit was established, through the mercury, and power input was reduced to a value such that the temperature would gradually decrease. This casued a decrease in the column height. When the higher electrode was no longer immersed in mercury, the circuit opened. This action caused a small sinusoidal variation about some fixed temperature

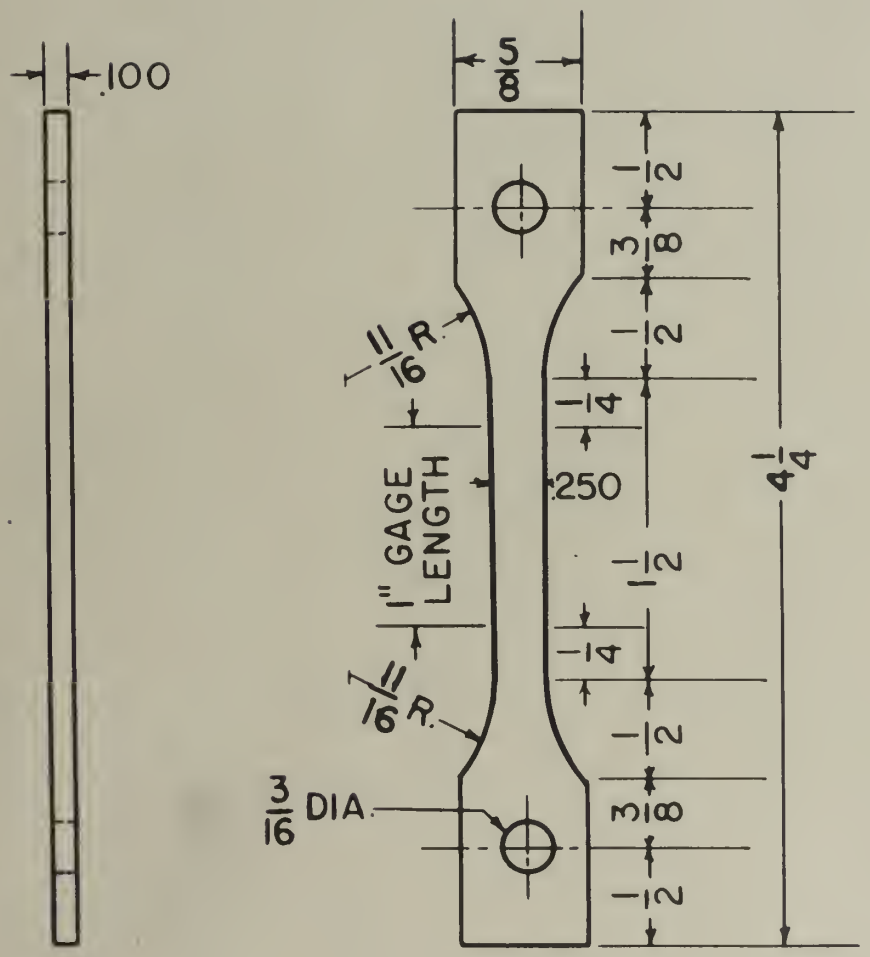


FIG. 4 TEST SPECIMEN

TABLE I

SPECTROGRAPHIC ANALYSIS*

| Element | Per Cent | Element | Per Cent |
|---|---|---|---|
| Manganese | 0.0001 | Tin | 0.001 |
| Antimony | 0.002 | Cadmium | 0.008 |
| Arsenic | 0.006 | Zinc | 0.004 |
| Lead | 0.001 | Titanium | 0.0002 |
| Magnesium | 0.001 | Silver | 0.01 |
| Iron | 0.001 | Zirconium | 0.003 |
| Bismuth | 0.001 | Nickel | 0.001 |
| Aluminum | 0.003 | Cobalt | 0.001 |
| Silicon | 0.003 | Chromium | 0.003 |

*Spectrographic analysis showed less than the above amounts. Chemical assay showed the material contained at least 99.97% copper. In the chemical assay, silver is counted as copper. In the spectrographic analysis, silver could not be estimated closely but it is probably less than 0.01%. In the spectrographic analysis, no lines corresponding to antimony, arsenic, cadmium, or zinc were found. The values given are the minimum amounts positively detectable, so conceivably the amounts of these elements present could be somewhat less than shown. It is unlikely that any are present in greater amounts than shown. The analyses were performed by the Industrial Laboratory, Mare Island Naval Shipyard, Vallejo, California.

determined by the amount of mercury originally in the bulb. Best temperature control was obtained when the bath level was such as to cover the entire bulb. No difficulty was experienced with vaporization of the silicone oil but it is felt that this could be a problem at temperatures greatly in excess of those reported on. In the low temperature region various baths, or environments, were attempted without success and will be commented on in a later section. In the only successful low temperature controlled tests, liquid nitrogen and liquid nitrogen-liquid oxygen binary mixtures were used. A four liter, cylindrical, dewar flask served as the container. Temperatures were measured in all cases by copper-constantan thermocouples with a Rubicon Portable Precision Potentiometer. Starrett, Model No. 656-T3, dial gages were used in the extensometer system.

Source and Treatment of Error

Thermocouples were mounted on the specimen at the top and bottom of the gage section. The temperature gradient across the gage length was constant at 0.1°K for the intermediate temperature tests, and 0.0°K for the low temperature tests. The sinusoidal variation of temperature, previously mentioned, had an amplitude of 0.1°K. The copper-constantan thermocouples were calibrated against precision thermometers from 293°K to 423°K, at the boiling point of nitrogen, at the boiling point of oxygen, and at the $CO_2$ sublimation point. The variation of voltage as a function of temperature between the boiling point of nitrogen and the boiling point of oxygen was treat-

ed as linear. In the measurement of temperature between 155°K and 273°K, a procedure described by Scott[27] was utilized. Potentiometer instrument error was regarded as negligible in the intermediate temperature region, and estimated not to exceed 0.2°K for the low temperature tests.

The dial gages used were long range instruments for this type of gage, the total possible gage travel being 0.42 inches. Minor dial divisions were $10^{-4}$ inches, making interpolation of $\pm$ 1 x $10^{-5}$ inches possible. A stepwise calibration, in steps of 0.1 inches, was made by means of Johansson blocks. The accummulative error, over 0.4 inches of travel, was minus 5 x $10^{-4}$ inches.

In the evaluation of the range of uncertainty in the determination of $\Delta H$ by equation (8), the error approximation of the differential calculus was used: $df = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy + \frac{\partial f}{\partial z} dz$. Utilizing this approach it is seen that the uncertainty in the strain rate determinations is magnified by the entire temperature term, $\left(\frac{T_1 T_2}{T_2 - T_1}\right)$. This term is evaluated as approximately 1.5 x $10^3$ for the low temperature tests and 1.3 x $10^4$ for the intermediate temperature tests. This then constitutes an extremely large percentage of the total uncertainty in the values calculated. This is particularly serious since the method utilized requires extrapolation of the creep curve through a period of temperature and gage transients. Only the data showing a minimum of these transients has been utilized and presented.

In the change of baths from $T_1$ to $T_2$ it was necessary to expose the specimen to room temperature, causing differential contraction and then expansion between the copper specimen and the stainless steel extensometer system. The usual time required for a bath change was 10 to 15 seconds. In order to isolate the effect of these transients, bath changes were made using both copper and stainless steel specimens with no load applied. Since the extensometer system was made of stainless steel, it was felt that substitution of a stainless steel specimen would eliminate any effect due to differences in material. When the stainless steel specimen was inserted, no gage transients were observed. Regardless of the time involved or the severity of the temperature transient, the gage reading remained constant. When the copper specimen was inserted in the system, this was no longer so. A gage transient appeared which varied in intensity and duration dependent on the temperature transient. For bath changes requiring up to 20 seconds to complete, the gage transient disappeared in less than two minutes. All data has been extrapolated through this region. The temperature transient in the intermediate temperature region was likewise dependent on the time required to change the baths, but had essentially disappeared in four to five minutes. The temperature at the end of this time was taken as $T_2$. Changing from a lower temperature to a higher temperature, the temperature was within $1^{\circ}K$ of the equilibrium value at the end of one minute, $0.3^{\circ}K$ at the end of two minutes, and within $0.1^{\circ}K$

at the end of four minutes. For the low temperature tests the temperature transient disappeared in less than one minute.

It was felt that a more intimate knowledge of the temperature transient would have been of great value in analyzing the data during the critical period. An attempt was made to record this transient but success was not realized. The thermocouple output was partially cancelled by a bridge potentiometer. The remainder of the voltage was fed to a direct current microvolt amplifier which fed a recorder. Success was not realized due to the basic instability and limited linearity of the amplifier. It is believed that the transient can be recorded in this manner if a more stable and more linear amplifier is available.

Low Temperature Problems

As originally planned, additional data was to be gathered at low temperatures, if time permitted. The method selected for temperature control was to utilize the melting point halts of various substances, since utilization of constant boiling or subliming materials was not found possible in this region, except for one series of tests which is presented. The problem which precludes the use of the materials chosen is believed to be general and encompass the great majority of the synthetic organic chemicals of the type presented in Table II. It is presented herein so that this pitfall may be avoided by others.

The chemicals listed in Table II were chosen to give pairs of bath temperatures, whose mean temperatures were approximately

TABLE II

LOW TEMPERATURE BATHS

| CHEMICAL | MELTING POINT $^{o}C$ |
|---|---|
| Diethylene Glycol | -8 |
| Ethylene Glycol | -13 |
| Diisobutyl Ketone | -36.5 |
| Ethyl Butyl Ketone | -41.5 |
| Ethylene Glycol Monomethyl Ether Acetate | -65.1 |
| Diethylene Glycol Monobutyl Ether | -68.1 |
| Ethylene Glycol Monomethyl Ether | -85.1 |
| n-Butyl Alcohol | -88.9 |
| Ethyl Ether | -116.3 |
| n-Butyl Chloride | -122.8 |

30 degrees Kelvin apart. Samples of these chemicals were tested in a dewar flask apart from the creep test system. They exhibited melting points approximately as listed and held a melting point halt for periods ranging from 30 minutes to several hours. Since the creep testing apparatus was being constructed at this time, the baths were not tested as an integral part of the system. The chemicals were found to be satisfactory for the purpose desired as regards corrosiveness and volatility. Diethylene glycol and ethylene glycol were found to be somewhat hygroscopic; but since no absolute temperature reference was necessary and the temperature difference appeared to be maintained, they were considered satisfactory.

The technique developed for utilizing these chemicals as constant temperature baths was simple and required only the equipment shown in Figure 5 and the cylindrical dewar flask. The large can was made out of stainless steel; the wire mesh cylinders and small can were copper. The inside dimensions of the large can are the same as the inside dimensions of the dewar flask, and the outside dimensions of the copper can are slightly greater than those of the small mesh cylinder. The inside dimensions of the small mesh cylinder are such as to just fit over the cage assembly (Figure 2). The large mesh cylinder and the copper can are placed in the large can and the liquid chemical poured around the copper can. The liquid is then chilled below its freezing point by placing solid $CO_2$ or liquid nitrogen in the inner can. When the liquid is frozen, it is removed by playing a small stream of water over the

Figure 5
LOW TEMPERATURE EQUIPMENT

stainless steel can and into the copper can. Surface melting allows removal of the cans and the solid may then be placed in the dewar. The small mesh cylinder is inserted in place of the copper can and the center of the solid is partially filled with liquid chemical that has been chilled to a temperature approaching its freezing point.

When the bath is isolated from the creep machine system, events occur as desired. However, when the cage and specimen assembly are inserted into the bath, the chemicals no longer exhibit a melting point halt. The cage assembly constitutes a rather large mass and must necessarily be chilled prior to its being surrounded by the bath. Various degrees of chilling were attempted, from subcooling of 100°K or more, to as little as 10 to 20°K. In every case the liquid center of the core subcooled a substantial amount (as much as 25°K) below its normal freezing point and remained liquid. No stirring was attempted, but some attempt at shaking was made. The system temperature rose slowly to some point 5 to 20 degrees below the predicted melting point; at which time the rate of temperature rise increased substantially and no melting point was observed.

The non-exhibition of a melting point halt under experimental test conditions precluded the use of these materials as a constant temperature environment and caused the discontinuance of further low temperature testing in this range. Successful tests were conducted at a lower temperature, however, using liquid nitrogen and a liquid nitrogen-liquid oxygen binary system for constant temperature environments.

# RESULTS AND CONCLUSIONS

A series of approximate activation energies for the creep of vacuum melted copper was determined. These were determined at mean temperatures of 78.5°K, 325.2°K, and 377.8°K, for several conditions of initial stress. These determinations are set forth in Table III. Attempts were made to determine this energy at temperatures between 155°K and 263°K utilizing the melting point of various synthetic organic chemicals, but these attempts were without success. While sufficient data has not been gathered to describe completely the variation of activation energy with temperature, some indication of the limits and trend, within the region tested, is shown. A plot of activation energy versus temperature, incorporating these results and those of Tietz and Dorn[24] is presented in Figure 6. A trend line is suggested. The basic experimental data is presented in the appendix. This data has been processed only to the extent that extensometer readings have been converted to strains and potentiometer microvolt readings have been converted to temperature.

The following conclusions are drawn:

1. The activation energies for creep of vacuum melted copper at intermediate and low temperatures are a function of temperature, with values substantially less than that of self-diffusion. They vary from approximately 4,500 cal/gm-mol in the vicinity of

TABLE III

TABULAR PRESENTATION OF RESULTS

| Tmean oK | $\sigma$ psi | $\Delta H_{1,2}$ cal/gm-mol |
|---|---|---|
| 78.5 | 40,000 | 5,700 ± 1,100 |
| | 40,000 | 4,350 ± 1,100 |
| | 44,000 | 4,150 ± 1,100 |
| 325.2 | 24,000 | 30,400 ± 3,000 |
| | 27,000 | 30,050 ± 3,000 |
| | 27,000 | 31,450 ± 3,000 |
| 377.8 | 18,000 | 34,750 ± 3,000 |
| | 23,900 | 33,450 ± 3,000 |
| | 23,900 | 35,050 ± 3,000 |

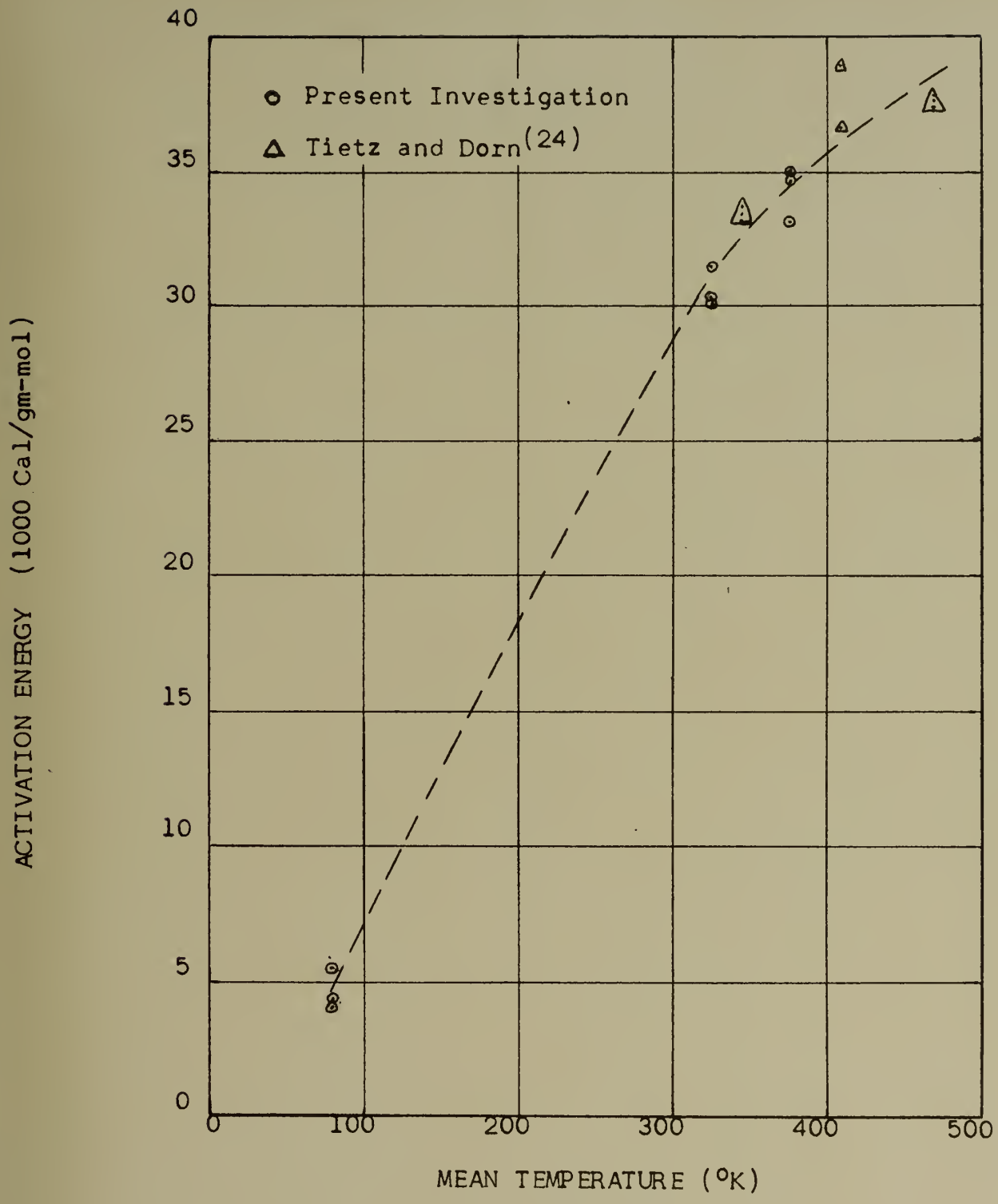


FIG. 6 ACTIVATION ENERGY VERSUS TEMPERATURE

78.5°K to approximately 34,500 cal/gm-mol in the vicinity of 378°K.

2. Although the data is somewhat limited, the activation energies determined appear to be independent of stress.

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BIBLIOGRAPHY


1. Sully, A.H. METALLIC CREEP AND CREEP RESISTANT ALLOYS, First Edition, 1949, Interscience Publishers, New York, pp. 1

2. A. S. M. METALS HANDBOOK, 1948, American Society for Metals, Cleveland, Ohio, pp. 4

3. Phillips, P. SLOW STRETCH IN INDIA RUBBER, GLASS, AND METAL WIRE, Philosophical Magazine, Vol. 9, 1905, pp. 513

4. Andrade, E.N. daC. THE VISCOUS FLOW IN METALS AND ALLIED PHENOMENA, PROCEEDINGS, Royal Society of London, Vol. 84A, 1910, pp. 1

5. Andrade, E.N. daC. FLOW IN METALS UNDER LARGE CONSTANT STRESS, PROCEEDINGS, Royal Society of London, Vol. 90A, 1914, pp. 329

6. Wyatt, O.H. PhD THESIS, 1950, Cambridge, England

7. Grant, N.J. CREEP AND FRACTURE AT ELEVATED TEMPERATURES, UTILIZATION OF HEAT RESISTANT ALLOYS, November 1954, American Society for Metals, Cleveland, Ohio, pp. 3

8. Hazlett, T.H. and Parker, E.R. NATURE OF THE CREEP CURVE, Journal of Metals, Vol. 5, 1953, pp. 318

9. Bragaw, C.G. Jr.. ScD THESIS, 1953, Massachusetts Institute of Technology, Cambridge, Mass.

10. Nadai, A. THE INFLUENCE OF TIME UPON CREEP. THE HYPERBOLIC SINE CREEP LAW, Stephen Timoshenko 60th Anniversay Volume, 1938, pp. 167

11. Eyring, H. VISCOSITY, PLASTICITY, AND DIFFUSION AS EXAMPLES OF ABSOLUTE REACTION RATES, Journal of Chemical Physics, Vol. 4, 1936, pp. 283

12. Kauzmann, W. FLOW OF SOLID METALS FROM THE STANDPOINT OF CHEMICAL RATE THEORY, TRANSACTIONS, A.I.M.E., Vol. 143, 1941, pp. 57

13. Dushman, S., Dunbar, L.W., & Huthsteiner, H. — CREEP OF METALS, Journal of Applied Physics, Vol. 15, 1944, pp. 108

14. Machlin, E.S. & Nowick, A.S. — STRESS RUPTURE OF HEAT RESISTANT ALLOYS AS A RATE PROCESS, TRANSACTIONS, A.I.M.E., Vol. 172, 1947, pp. 386

15. Grant, N.J. & Bucklin, A.C. — ON THE EXTRAPOLATION OF SHORT-TIME STRESS-RUPTURE DATA. TRANSACTIONS, A.S.M., Vol. 42, 1950, pp. 720

16. Larson, F.R. & Miller, J. — A TIME-TEMPERATURE RELATIONSHIP FOR RUPTURE AND CREEP STRESSES, TRANSACTIONS, A.S.M.E., Vol. 74, 1952, pp. 765

17. Sietz, F. & Read, T.A. — THEORY OF THE PLASTIC PROPERTIES OF SOLIDS, Journal of Applied Physics, Vol. 12, 1941, pp. 100, 170, 470, 538

18. Mott, N.F. — THEORIES OF THE MECHANICAL PROPERTIES OF METALS, Research, Vol. 2, 1949, pp. 162

19. Nabarro, F.R.N. — NEUERE ENGLISCHE ARBEITEN UBER DIE VERSETZUNGSTHEORIE DER GLEITUNG, ZS METALK, Vol. 40, 1949, pp. 81

20. Orowan, E. — THE CREEP OF METALS, Journal, West of Scotland Iron and Steel Institute, February 1947, pp. 45

21. Cottrell, A.E. — THEORY OF DISLOCATIONS, Progress in Metal Physics, Vol. 1, 1949, Interscience Publishers, Inc., New York, pp. 77

22. Sherby, O.D. & Dorn, J.E. — AN ANALYSIS OF THE PHENOMENON OF HIGH TEMPERATURE CREEP, Institute of Engineering Research, University of California, 34th Technical Report, 15 January 1954, pp. 9

23. Sherby, O.D., Orr, R.L., & Dorn, J.E. — CREEP CORRELATIONS OF METALS AT ELEVATED TEMPERATURES, Journal of Metals, A.I.M.E., January 1954, pp. 71-80

24. Tietz, T.E. & Dorn, J.E. — CREEP OF COPPER AT INTERMEDIATE TEMPERATURES, Institute of Engineering Research, University of California, 38th Technical Report, 15 September 1954, pp. 10

25. Naczkowski, B.R. CREEP BEHAVIOR OF MAGNESIUM AT LOW TEMPERATURES, M. S. Thesis, 1955, U.S. Naval Postgraduate School, Monterey, California

26. Dorn, J.E. LECTURE, Applied Mechanics Division, A.S.M.E., Stanford University, 12 January 1956

27. Scott, R.B. THE CALIBRATION OF THERMOCOUPLES AT LOW TEMPERATURES; TEMPERATURE, ITS MEASUREMENT AND CONTROL, IN SCIENCE AND INDUSTRY, American Institute of Physics, 1941, pp. 206

# APPENDIX

## TABULAR PRESENTATION OF DATA

### Test No. 1

Initial Stress 23,850 psi

| Time (minutes) | Strain (inches/inch) | Temperature (°K) |
|---|---|---|
| 1.0 | .12329 | 372.1 |
| 1.5 | .12539 | |
| 2.0 | .12649 | |
| 2.75 | .12877 | |
| 3.25 | .12937 | |
| 3.75 | .12979 | |
| 4.25 | .13026 | |
| 5.25 | .13105 | |
| 6.25 | .13170 | |
| 7.25 | .13229 | |
| 8.25 | .13278 | |
| 9.25 | .13325 | |
| 11.25 | .13416 | |
| 13.25 | .13419 | |
| 15.25 | .13571 | 372.2 |
| 17.25 | .13639 | |
| 22.25 | .13788 | |
| 27.25 | .13910 | |
| 32.25 | .14010 | |
| 37.25 | .14099 | |
| 42.25 | .14199 | 372.3 |
| 47.25 | .14276 | |
| 52.25 | .14359 | |
| 54.25 | .14388 | |
| 56.25 | .14414 | 372.2 |
| 58.25 | .14440 | |
| 60.25 | .14463 | 372.2 |
| Change Baths | | |
| 62.25 | .14512 | |
| 63.25 | .14546 | 383.0 |
| 64.25 | .14587 | 383.2 |
| 65.25 | .14632 | |
| 66.25 | .14667 | |
| 67.25 | .14708 | |
| 69.25 | .14787 | 383.2 |
| 71.25 | .14842 | |
| 74.25 | .14941 | |
| 77.25 | .15018 | |
| 82.25 | .15131 | |
| 87.25 | .15251 | 383.3 |
| 92.25 | .15351 | |
| 97.25 | .15425 | |
| 99.25 | .15467 | 383.2 |
| 101.25 | .15500 | |

TABULAR PRESENTATION OF DATA Cont.

Test No. 2

Initial Stress 23,900 psi

| Time (minutes) | Strain (inches/inch) | Temperature (°K) |
|---|---|---|
| 0.5 | .12928 | 372.2 |
| 1.0 | .13026 | |
| 1.5 | .13107 | |
| 2.0 | .13163 | |
| 2.5 | .13219 | |
| 3.0 | .13269 | |
| 3.5 | .13319 | |
| 4.5 | .13400 | |
| 5.5 | .13526 | 372.1 |
| 7.5 | .13594 | |
| 9.5 | .13683 | |
| 11.5 | .13776 | |
| 14.5 | .13885 | |
| 17.5 | .13979 | |
| 20.5 | .14064 | |
| 23.5 | .14148 | |
| 27.5 | .14238 | |
| 32.5 | .14355 | 372.2 |
| 37.5 | .14459 | |
| 43.0 | .14557 | |
| 47.5 | .14628 | 372.3 |
| 52.5 | .14708 | |
| 54.5 | .14738 | |
| 56.5 | .14767 | 372.2 |
| 58.5 | .14791 | 372.2 |
| Change Baths | | |
| 59.5 | .14830 | |
| 60.0 | .14840 | 383.0 |
| 60.5 | .14866 | |
| 61.0 | .14888 | |
| 61.5 | .14908 | |
| 62.0 | .14931 | 383.1 |
| 62.5 | .14960 | |
| 63.0 | .14986 | |
| 63.5 | .15008 | |
| 64.5 | .15059 | |
| 65.5 | .15098 | 383.1 |
| 66.5 | .15144 | |
| 68.5 | .15218 | |
| 70.5 | .15297 | |
| 73.5 | .15397 | 383.2 |
| 76.5 | .15498 | |
| 80.5 | .15603 | |
| 83.5 | .15679 | 383.1 |
| 87.5 | .15768 | |

TABULAR PRESENTATION OF DATA Cont.

Test No. 3

Initial Stress 18,000 psi

| Time (minutes) | Strain (inches/inch) | Temperature (°K) |
|---|---|---|
| 0.25 | .05039 | 372.6 |
| 1.0 | .05205 | |
| 2.0 | .05266 | |
| 2.5 | .05287 | |
| 3.0 | .05300 | |
| 3.5 | .05312 | |
| 4.0 | .05323 | |
| 5.0 | .05343 | |
| 7.0 | .05378 | |
| 9.0 | .05398 | 372.7 |
| 12.0 | .05424 | |
| 15.0 | .05428 | |
| 19.0 | .05450 | |
| 23.0 | .05476 | 372.6 |
| 27.0 | .05491 | |
| 32.0 | .05518 | |
| 37.0 | .05534 | |
| 43.0 | .05555 | |
| 49.0 | .05570 | 372.5 |
| 57.0 | .05591 | |
| 67.0 | .05616 | |
| 80.0 | .05642 | 372.6 |
| 94.0 | .05670 | 372.6 |
| Change Baths | | |
| 96.0 | .05698 | |
| 97.0 | .05699 | 383.3 |
| 98.0 | .05705 | 383.4 |
| 100.0 | .05711 | |
| 102.0 | .05722 | |
| 104.0 | .05730 | 383.4 |
| 107.0 | .05746 | |
| 110.0 | .05758 | |
| 116.0 | .05787 | 383.5 |
| 122.0 | .05806 | |
| 128.0 | .05827 | |
| 137.0 | .05849 | 383.4 |
| 147.0 | .05874 | |
| 157.0 | .05891 | |
| 167.0 | .05919 | 383.3 |
| 177.0 | .05933 | |
| 187.0 | .05959 | |
| 197.0 | .05977 | |
| 208.0 | .05987 | 383.4 |
| 217.0 | .06000 | |

TABULAR PRESENTATION OF DATA Cont.

Test No. 4

Initial Stress 24,000 psi

| Time (minutes) | Strain (inches/inch) | Temperature (°K) |
|---|---|---|
| 1.0 | .10483 | 320.8 |
| 1.5 | .10530 | |
| 2.0 | .10561 | 320.9 |
| 2.5 | .10589 | |
| 3.0 | .10609 | |
| 4.0 | .10639 | |
| 5.0 | .10662 | |
| 6.0 | .10683 | |
| 8.0 | .10718 | |
| 10.0 | .10744 | |
| 13.0 | .10773 | 320.8 |
| 16.0 | .10799 | |
| 20.0 | .10826 | |
| 24.0 | .10847 | |
| 29.0 | .10871 | 320.9 |
| 34.0 | .10889 | |
| 41.0 | .10918 | 321.0 |
| 47.0 | .10936 | |
| 55.0 | .10958 | 320.9 |
| Change Baths | | |
| 57.0 | .10971 | |
| 59.0 | .10991 | 329.2 |
| 61.0 | .11008 | |
| 62.0 | .11014 | |
| 64.0 | .11029 | 329.2 |
| 67.0 | .11047 | |
| 72.0 | .11077 | 329.3 |
| 77.0 | .11102 | |
| 82.0 | .11129 | 329.3 |
| 92.0 | .11168 | |
| 101.0 | .11200 | 329.2 |
| 112.0 | .11231 | |
| 122.0 | .11258 | |

TABULAR PRESENTATION OF DATA Cont.

Test No. 5

Initial Stress 27,000 psi

| Time (minutes) | Strain (inches/inch) | Temperature (°K) |
|---|---|---|
| 1.0 | .12652 | 321.1 |
| 2.0 | .13077 | |
| 2.5 | .13165 | |
| 3.0 | .13232 | 321.2 |
| 3.5 | .13290 | |
| 4.0 | .13335 | |
| 5.0 | .13411 | |
| 6.0 | .13474 | |
| 7.0 | .13526 | |
| 8.0 | .13572 | |
| 9.5 | .13633 | |
| 11.0 | .13687 | 321.3 |
| 13.0 | .13753 | |
| 15.0 | .13809 | |
| 18.0 | .13876 | |
| 21.0 | .13935 | |
| 25.0 | .14011 | |
| 29.0 | .14073 | |
| 33.0 | .14127 | |
| 38.0 | .14191 | 321.2 |
| 43.0 | .14247 | |
| 48.0 | .14299 | |
| 53.0 | .14344 | |
| 58.0 | .14391 | 321.1 |
| 63.0 | .14433 | |
| 68.0 | .14472 | |
| 73.0 - | .14511 | 321.2 |
| 78.0 | .14542 | |
| 79.0 | .14549 | 321.2 |
| Change Baths | | |
| 81.0 | .14580 | |
| 82.0 | .14601 | 329.2 |
| 83.0 | .14623 | |
| 84.0 | .14648 | 329.3 |
| 85.0 | .14669 | |
| 88.0 | .14732 | |
| 90.0 | .14771 | |
| 93.0 | .14832 | 329.2 |
| 96.0 | .14883 | |
| 99.0 | .14931 | |
| 103.0 | .14994 | 329.1 |
| 107.0 | .15052 | |
| 111.0 | .15103 | |
| 115.0 | .15149 | 329.2 |
| 121.0 | .15218 | |
| 126.0 | .15271 | 329.3 |
| 131.0 | .15312 | |
| 136.0 | .15372 | |
| 141.0 | .15420 | 329.2 |

TABULAR PRESENTATION OF DATA Cont.

Test No. 6

Initial Stress 27,000 psi

| Time (minutes) | Strain (inches/inch) | Temperature ($^{o}K$) |
|---|---|---|
| 1.0 | .14158 | 321.3 |
| 1.5 | .14543 | |
| 2.0 | .14688 | |
| 2.5 | .14786 | |
| 3.0 | .14858 | |
| 4.0 | .14964 | |
| 5.0 | .15037 | |
| 6.0 | .15098 | 321.2 |
| 8.0 | .15201 | |
| 10.0 | .15276 | |
| 12.0 | .15338 | |
| 14.0 | .15397 | |
| 17.0 | .15464 | |
| 20.0 | .15526 | 321.1 |
| 23.0 | .15577 | |
| 26.0 | .15627 | |
| 29.0 | .15668 | |
| 32.0 | .15712 | |
| 36.0 | .15764 | 321.2 |
| 40.0 | .15813 | |
| 45.0 | .15868 | |
| 50.0 | .15917 | 321.3 |
| 56.0 | .15969 | |
| 59.0 | .15998 | |
| 62.0 | .16019 | 321.2 |
| Change Baths | | |
| 63.0 | .16036 | |
| 64.0 | .16047 | |
| 65.0 | .16070 | 329.3 |
| 66.0 | .16099 | |
| 67.0 | .16126 | |
| 68.0 | .16150 | 329.4 |
| 70.0 | .16203 | |
| 72.0 | .16249 | |
| 74.0 | .16294 | 329.3 |
| 76.0 | .16336 | |
| 78.0 | .16373 | |
| 81.0 | .16429 | |
| 84.0 | .16479 | |
| 87.0 | .16529 | 329.2 |
| 90.0 | .16571 | |
| 94.0 | .16629 | |
| 98.0 | .16682 | |
| 102.0 | .16732 | 329.3 |
| 106.0 | .16779 | |
| 110.0 | .16827 | |
| 115.0 | .16879 | |
| 120.0 | .16934 | 329.4 |
| 125.0 | .16978 | |

TABULAR PRESENTATION OF DATA Cont.

Test No. 7

Initial Stress 40,000 psi

| Time (minutes) | Strain (inches/inch) | Temperature (°K) |
|---|---|---|
| 1.0 | .19272 | 77.4 |
| 1.5 | .19477 | |
| 2.0 | .19515 | |
| 2.5 | .19543 | |
| 3.0 | .19560 | |
| 4.0 | .19587 | |
| 5.0 | .19606 | |
| 7.0 | .19633 | |
| 9.0 | .19660 | 77.4 |
| 11.0 | .19675 | |
| 14.0 | .19694 | |
| 18.0 | .19713 | |
| 22.0 | .19731 | |
| 26.0 | .19744 | |
| 30.0 | .19754 | |
| 40.0 | .19775 | |
| 50.0 | .19794 | |
| 60.0 | .19811 | 77.4 |
| Change Baths | | |
| 62.0 | .19817 | 81.1 |
| 62.5 | .19823 | |
| 63.0 | .19831 | |
| 64.0 | .19838 | 81.1 |
| 66.0 | .19849 | |
| 69.0 | .19862 | |
| 73.0 | .19875 | |
| 80.0 | .19894 | 81.1 |
| 90.0 | .19914 | |
| 105.0 | .19939 | |
| 120.0 | .19960 | 81.1 |

TABULAR PRESENTATION OF DATA Cont.

Test No. 8

Initial Stress 40,000 psi

| Time (minutes) | Strain (inches/inch) | Temperature ($^{o}K$) |
|---|---|---|
| 1.0 | .20090 | 77.4 |
| 1.5 | .20211 | |
| 2.0 | .20256 | |
| 3.0 | .20300 | |
| 4.0 | .20327 | |
| 5.0 | .20345 | 77.4 |
| 7.0 | .20367 | |
| 9.0 | .20381 | |
| 12.0 | .20401 | |
| 17.0 | .20422 | |
| 22.0 | .20441 | 77.4 |
| 32.0 | .20473 | |
| 42.0 | .20492 | |
| 52.0 | .20506 | |
| 60.0 | .20519 | 77.4 |
| Change Baths | | |
| 62.5 | .20528 | 81.0 |
| 64.0 | .20536 | |
| 67.0 | .20548 | |
| 72.0 | .20568 | 81.0 |
| 77.0 | .20584 | |
| 87.0 | .20610 | |
| 97.0 | .20631 | |
| 107.0 | .20645 | 81.0 |
| 117.0 | .20659 | 81.0 |

TABULAR PRESENTATION OF DATA Cont.

Test No. 9

Initial Stress 44,000 psi

| Time (minutes) | Strain (inches/inch) | Temperature (°K) |
|---|---|---|
| 1.0 | .23994 | 77.6 |
| 1.5 | .24229 | |
| 2.0 | .24294 | |
| 2.5 | .24345 | |
| 3.0 | .24377 | |
| 4.0 | .24424 | |
| 5.0 | .24455 | |
| 6.0 | .24492 | |
| 7.0 | .24517 | |
| 8.0 | .24535 | |
| 9.0 | .24551 | |
| 11.0 | .24580 | 77.6 |
| 14.0 | .24608 | |
| 17.0 | .24634 | |
| 21.0 | .24656 | |
| 25.0 | .24672 | |
| 30.0 | .24693 | 77.6 |
| 35.0 | .24714 | |
| 40.0 | .24733 | |
| 50.0 | .24764 | |
| 60.0 | .24789 | 77.6 |
| Change Baths | | |
| 62.0 | .24814 | 81.5 |
| 65.0 | .24841 | |
| 68.0 | .24862 | |
| 71.0 | .24891 | |
| 76.0 | .24915 | 81.5 |
| 81.0 | .24939 | |
| 86.0 | .24960 | |
| 91.0 | .24980 | |
| 96.0 | .24995 | 81.5 |
| 106.0 | .25026 | |
| 116.0 | .25051 | 81.5 |